The performance of an idealized large-area array of moderate-sized IACTs

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Abstract: We present simulations of a large array of imaging atmospheric Cherenkov telescopes (IACTs), for which the size of the array footprint is much larger than the size of the Cherenkov lightpool. To evaluate limitations of the imaging atmospheric Cherenkov technique, the array is simulated under the assumption of ideal optics, having infinite resolution of the photon arrival direction, which makes our conclusions independent of any particular telescope implementation. The primary characteristics of the array performance, γ-ray trigger efficiency, photon energy at the peak of the detection rate, and angular resolution are calculated as a function of the parameters of the array: telescope spacing, telescope aperture, and camera pixelation. We discuss implication of the results for the design of the next generation ground-based γ-ray observatory.

Introduction

Next generation ground-based γ-ray observatories, such as AGIS and CTA, will likely consist of an array of on the order of 100 telescopes, spread over an area potentially exceeding 1km^2 on the ground. A starting point for understanding the response of such instruments is to simulate a large array of identical telescopes, with the parameters of the array covering the range that is reasonable from the point of view of cost, practicability of construction, and scientific return. This constrains the effective light collecting area of the individual telescopes to the range between 20 m^2 to 200 m^2, the separation between telescopes to the range of 80 m and 217 m and the pixel size in the camera to the range from 1 arc minute to 16 arc minutes.

The large-area array will operate in a different regime to the current generation instruments, VERITAS and H.E.S.S. [5, 1]. Significantly above 100 GeV the array will have a collecting area greater than its footprint on the ground, giving it a sensitivity an order of magnitude larger than VERITAS at high energies. Because the footprint of such an array is much larger than the characteristic size of the Cherenkov light-pool from an electromagnetic cascade in the atmosphere, it will take advantage of the "cell effect", significantly improving its response at energies lower than 100 GeV [3]. Finer pixelation of the cameras of the individual telescopes will further increase the sensitivity, especially at lower energies. This increase arises from both the improved angular resolution and increased background rejection. In this paper we investigate the cell and pixel effects numerically.

Simulations

Quasi-infinite arrays of hexagonally packed Cherenkov telescopes were simulated. The arrays are described by two parameters, the separation between telescopes, L, and the effective diameter of each telescope, D, assuming an effective light collection area of $\frac{\pi}{4}D^2$. We simulate arrays with all combinations of $L = \{80, 91, 106, 128, 160, 213\}$ m and $D = \{5, 7, 10, 15\}$ m.

The simulations employed the CORSIKA air-shower package [2] to generate Cherenkov photons at 3500 m elevation. An idealized telescope optical model, with zero dispersion due to PSF, was assumed. Light losses due to reflections at two aluminum mirrors and inefficient conversion to photoelectrons at a standard bi-alkali photocathode were included. The telescopes were allowed to

have different triggering and imaging pixel scales. It was previously found that the optimal pixel size on the triggering sensor is between $\sim 0.05^\circ$ and $\sim 0.25^\circ$, and is relatively independent of L and D [3]; we chose a value of $\sim 0.15^\circ$ in this simulation. The trigger threshold is set to give a 250 Hz per-telescope rate of accidental triggers from night sky noise in the 7° field of view. The array is triggered when three telescopes detect a simulated event. Since we have assumed an ideal optical system, we investigated the effects of PSF and pixelation in the imaging sensor by quantizing the arrival direction of the Cherenkov photons into pixels once they reach the telescope. Pixel sizes of $P = \{1, 2, 4, 8, 16\}$ arc minutes were chosen for study. The cleaning procedure, which was based on the density of photoelectrons in the image, was independently optimized for each pixel size to achieve the best reconstruction of events.

As the array is assumed to be effectively infinite we take advantage of the translational symmetry between the hexagonal cells in the array to simplify the simulations. We use CORSIKA to generate γ-ray events that impact within one "central" hexagonal cell of the array. Since in this study we are primarily interested in the response of the array at low energies, only those telescopes within ~ 600 meters of the central cell were simulated. More distant telescopes do not contribute to the triggering and reconstruction of γ-ray events at low energy.

Results

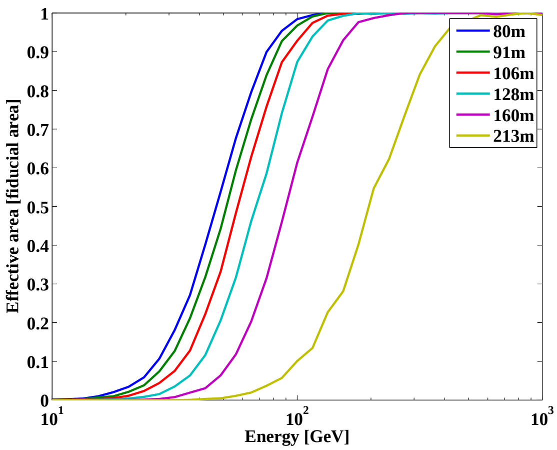
Figure 1 shows the triggering efficiency as a function of γ-ray energy (left), and the differential rate of γ-rays from a source with a Crab Nebula-like spectrum (right) for arrays with $D = 7$ m with different telescope separations. In the highest energy regime, the response of each configuration is saturated, with the trigger efficiency reaching 1.0 in each case, and the arrays are indistinguishable in this sense. In a real array, events impacting near to the perimeter will modify the triggering efficiency. The significance of this effect is a function of the ratio of the area of the Cherenkov light pool to the area of the array. It is likely that, at the highest energies, a 1 km^2 array would have a collecting area significantly larger than its physical area on the ground.

At lower energies the triggering efficiency, and hence the collecting area of the array for γ-rays, declines. For a VERITAS-like array the collecting area at low energies is a strong function of energy due to the exponentially declining density of photons outside of the central region of the Cherenkov light pool. For large arrays, in which the telescope separation is smaller than characteristic Cherenkov diameter, photons are always "sampled" within the central region of the Cherenkov light-pool, in which their density is a weak function of energy. Due to this "cell effect", the fall-off in the detection rate below the peak energy (E_{peak}) is considerably slower than for a VERITAS-like instrument, and this provides appreciably better sensitivity at low energies. Figure 1 (right) shows that for the $L = 80$ m, $D = 7$ m configuration, $E_{\mathrm{peak}} \approx 42$ GeV and the detection rate exceeds 50% of its peak value within the range from ~ 18 GeV to ~ 80 GeV.

The results from all the configurations are combined in figure 2, which shows E_{peak} as a function of the ratio of the effective mirror diameter to the separation between telescopes in the array (D/L). An unexpected finding was that E_{peak} is primarily determined by the single parameter D/L, being largely degenerate in the direction of $D \times L$. This non-trivial result has a direct implication on the design of future large arrays, which may be required to achieve some specific E_{peak}, as determined by the scientific goals of the experiments. This requirement on E_{peak} translates directly onto a requirement on the ratio of D/L,

$$\left(\frac{D}{7\,\mathrm{m}}\right)\left(\frac{80\,\mathrm{m}}{L}\right) = \left(\frac{E_{\mathrm{peak}}}{36\,\mathrm{GeV}}\right)^{-0.77}$$

Figure 3 shows the effects that increasing pixelation have on the ability of the array to reconstruct the arrival direction of a primary γ-ray. For 1 arc minute pixels the signal-to-background ratio reaches a maximum at approximately 7 and 3.8 minutes of arc from the source location for 40 and 100 GeV photons respectively. With 8 arc minute pixels, slightly smaller than those of current generation instruments such as VERITAS, the ratio reaches a maximum value at approximately 10 and 5 minutes of arc. The relative amplitude of the



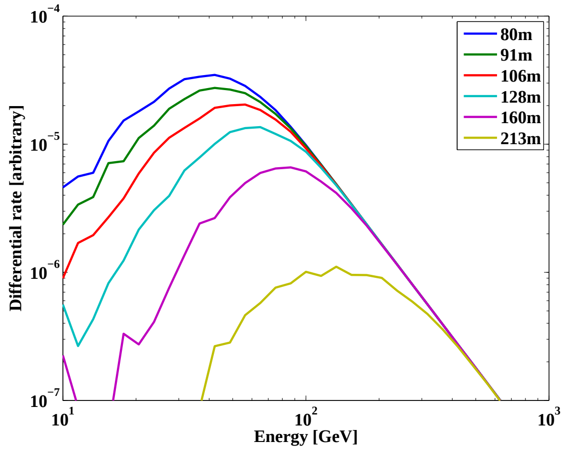


Figure 1: Left: trigger collecting efficiency as a function of energy for γ-ray events impacting a cell in an infinite hexagonal telescope array, for various telescope separations. Each telescope has an effective diameter of 7 m and an idealized optical response. Right: differential rate of detected γ-rays from a source with a Crab Nebula-like spectrum.

peaks indicate reduction of the instrument sensitivity by $\sim 40\%$.

Our simulations confirm that the angular resolution of the reconstructed arrival direction improves with finer pixelation of the camera until the typical angular scale determined by the transverse size of the shower core is reached. This size is approximately a few minutes of arc, as the core, consisting of the highest energy particles in the cascade, has an extent of a few meters [4], and the typical observing distance of 100 GeV cascades is on the order of 10 km.

Conclusions

A large array of Atmospheric Cherenkov Telescopes will operate in a very different regime to VERITAS and H.E.S.S. at low energies. The response is improved largely due to the “cell effect”, enabling a significant reduction to the peak detection energy, $E_{\rm peak}$. This parameter, constrained by the scientific goal of the future instrument, fixes the ratio of D/L for the array, through a non-trivial scaling law. Decrease of the camera pixel size to 1 arc minute improves the reconstruction of the photon arrival direction, and therefore the signal to noise ratio. Considerations of cost, however, will determine the final design of the future instrument.

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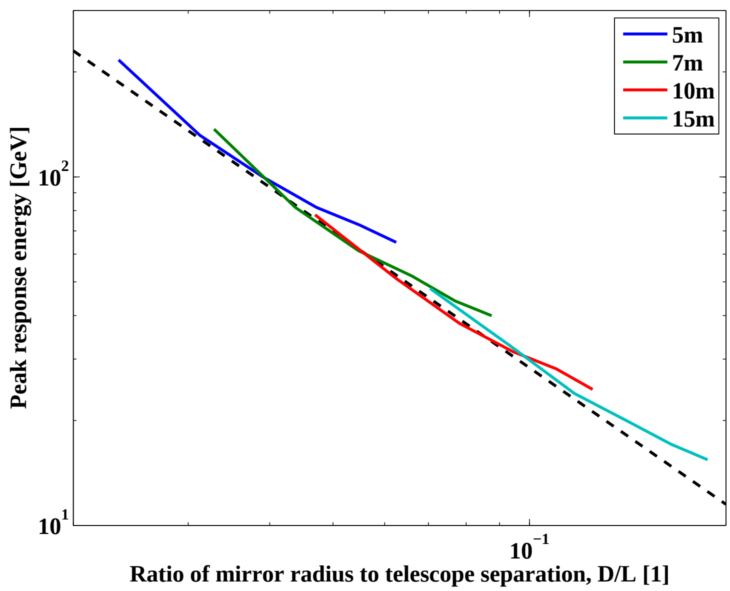

Figure 2: Peak response energy, E_{peak}, of a large array as a function of the ratio of the effective mirror diameter, D, to the telescope separation, L (solid curves). The curves lie approximately on the power-law relation $E_{\mathrm{peak}} = 240\,\mathrm{GeV}\left(\frac{D/L}{0.02}\right)^{-1.3}$.

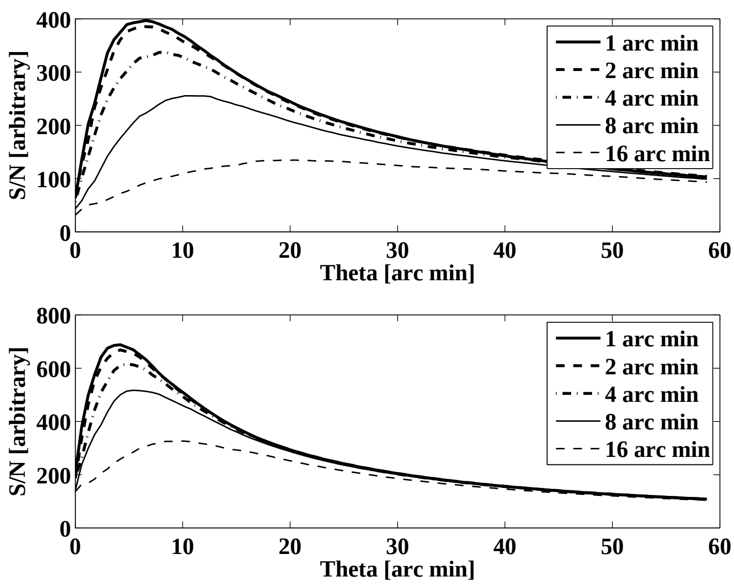

Figure 3: Ratio of the number of γ-ray events reconstructed within angular distance θ of the source to square root of the number of background events in the same region. Two figures show the results of simulations for 40 and 100 GeV photons. An array of 75 m^2 telescopes with separation of 80 m was assumed.